NASA TECHNICAL TRANSLATION NASA TT F-14,208

UNSOLVED PROBLEMS OF AIRPLANE AERODYNAMICS

J. Barche

Translation of "Offene Probleme der Flugzeug-Aerodynamik". Deutsche Gesellschaft für Luft-und Raumfahrt, Jahrestagung, 4th, Baden-Baden, W. Germany, Oct. 11 - 13, 1971, Paper 71-105. 32 pages.

(NASA-TT-F-14208) UNSOLVED PROBLEMS OF AIRPLANE AERODYNAMICS J. Barche (Scientific Translation Service) Mar. 1972 51 p CSCL 01A G3/01

N72-19993

Unclas 23057

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 MARCH 1972

TABLE OF CONTENTS

	Page
1. Introduction	1
2. Processing of Aerodynamic Projects	3
2.1. Time History of Processing	3
2.2. Treatment Method	6
3. Special Unsolved Problems	9
3.1. Flight Phases and Flight Ranges	9
3.2. Takeoff and Landing	10
3.2.1. Short Takeoff and Landing Using High-lift Auxiliary Devices	10
3.2.2. Vertical Takeoff and Landing by Jet Support	16
3.3. Transonic Cruise	26
3.4. Maneuvering Flight in the Subsonic and Transonic Flow Regime	30
4. Summary	38
5. References	39
6. Appendix	42

UNSOLVED PROBLEMS OF AIRPLANE AERODYNAMICS[1]

J. Barche[2]

Problems inherent in current and future aircraft design which still lack a solution as a result of gaps in the theoretical and experimental description of flow patterns are discussed. Both civil and military aircraft in the subsonic and transonic range are considered. Problems arising in different phases of aerodynamic design are examined first. Next, special flow problems encountered during different flight phases, such as takeoff and landing, during transonic flight, and during flight maneuvers, are characterized and explained.

1. Introduction

"Aircraft can be developed in all industrial countries. The rules of aircraft construction have become technical information which is available to all. This means that all basic problems have been solved and there are no longer any 'unsolved problems'!"

---

[1]Presented at the Fourth Annual Meeting of the DGLR (German Association for Aerodynamics and Space Flight), Baden-Baden, October 11 - 13, 1971, Lecture No. 71-105.

[2]Associated Aerodynamic Plants Fokker, GmbH, Bremen, West Germany.

Translator's Note: Original paper not page numbered.

This idea is sometimes heard even in specialist circles. This is especially true when unsolved problems in aerodynamics are presented.

However, substantial advances in aircraft construction have been the result of aerodynamic research. This is why aerodynamic research must address itself to new problems and cannot limit itself to look for solutions to problems in previous work.

Instead, it makes much more sense to limit the work spectrum to the available resources. For example, at this point it does not seem appropriate to discuss unsolved problems in supersonic or even hypersonic commercial aircraft, as long as it is unrealistic to assume that Germany will participate substantially in the development of such aircraft.

This is why in the following we have selected certain problems associated with commercial and military aircraft in the subsonic and transonic range. Since there is a certain degree of arbitrariness in the selection, additional problems have been summarized in table form in the Appendix.

2. Processing of Aerodynamic Projects

2.1. Time History of Processing

Only in a few cases are unsolved problems in aircraft development tackled because of scientific interest. As a rule, they automatically appear by themselves during certain phases of processing of an aircraft design. The scale of problems confronted ranges from predesign problems associated with development of a design goal up to brief measures which are encountered during flight tests. This can be represented in a diagram which shows the individual work phases during the development of an aircraft project.

Figure 1 shows such a diagram. It stresses the treatment of the aerodynamic problems, but is also valid for other disciplines associated with the project.

The treatment begins by establishing the design goal. The goal can be specified by a customer, can be dictated by the market, or can be determined independently.

A design goal can be reached in various ways in general. Since an aircraft represents a compromise between individual design disciplines, the best compromise should be found in a predesign or concept phase of the project.

For this purpose, the aerodynamicist requires input parameters in order to perform the predesign work. On the other hand, he must support his associates with aerodynamic data. The concept phase therefore is associated with an iteration

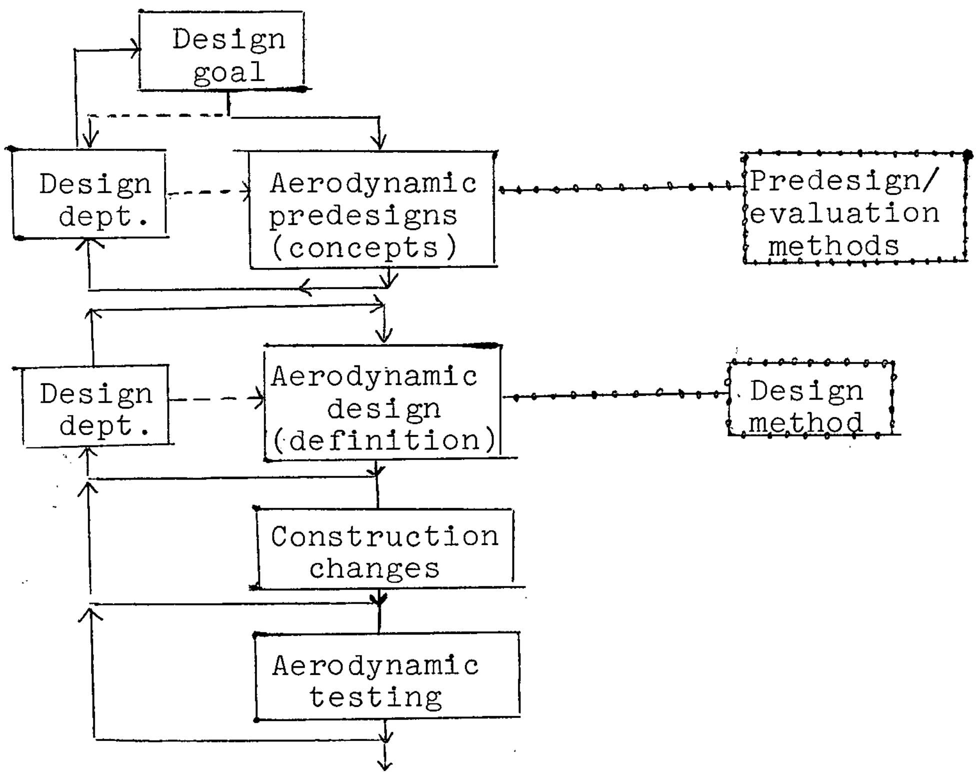

Figure 1. Aerodynamic project treatment

loop. Theoretically, it could remain in motion continuously, if it were not for the fact that this phase is especially subject to time and cost pressures. The so-called point designs are the result of this concept phase, which verify that the design goal can be achieved within a certain margin of error. They also lead to certain conclusions or can result in a cancellation of certain requirements for the project.

After the concept phase is concluded, and providing the work is continued, the design or definition phase begins. This phase usually extends over a considerable time period and serves to work out the ideas developed during the predesign phase. As far as the aerodynamicists are concerned, it is terminated with a detailed definition of the external shape of an aircraft.

This process has a similar course as the predesign phase as far as its association with other development work is concerned. Information is continuously required from the aerodynamicists here as well, and he is also required to continuously support his colleagues with new information.

The results of the definition phase are continuously compared with the nominal values of the point designs and the design goals. Often it is found that the data of the point design were too optimistic. For some designs, the work must be terminated for this reason.

The third phase in the processing of an aircraft design is called the development phase, in which the detailed construction data are developed and prototypes are built.

Quite often during this phase it is established that ideas set forth by the aerodynamicists can only be realized at substantial construction effort and costs. Very often the construction change requirements are so great during this phase that the design goal must be compromised.

The most severe test of the quality of the aerodynamic work occurs during the flight test phase. Since the possibilities for making changes are extremely limited during this phase, aerodynamic errors are expressed in the most pronounced way on the certification papers, which specify the subsequent performance and characteristics. These can then be compared with the design data.

2.2. Treatment Method

The aerodynamicists require methods and processes for treatment of a project which can be divided into the following three groups:

theoretical methods
experimental methods, and
empirical-statistical methods

These methods should already be established when the design goal is established. At the latest, they should be available during the subsequent phases. This can mean that a design goal can only be defined when the required fundamental knowledge is developed in the predesign studies. As an example, we can refer to the preliminary work for the VTOL-transport aircraft.

The working methods of the aerodynamicists must satisfy different requirements during the individual phases of the project:

In the predesign phase there are methods for rapid determination and evaluation of the main parameters and the overall coefficients of competing designs, from which the point designs mentioned above are developed. The methods must therefore be rapid and flexible ones. Within certain limits, this can be done at the expense of accuracy. Experimental investigations are carried out relatively infrequently for the reasons mentioned above. Often it is not possible to use extensive and complex computation methods for the calculation of viscous and invicid flows around bodies for the same reason.

In the predesign phase it is primarily necessary to use simple computation methods and empirical-statistical methods. These can be found in handbooks (for example, [1], [2]) or numerous company-internal working papers and predesign methods. These handbooks have gaps in those areas which are continuously in flux or which have been added over the last few years. High-lift and VSTOL-technology are typical examples of this. It would be very valuable to supplement the methods in these areas so that the predesign work could be carried out (3).

In addition to the concept phase, work during the definition phase requires an accurate knowledge of the local flow conditions and higher order coefficients for the planned aircraft. Usually experimental and also theoretical methods must be used for this.

The theoretical methods are especially remarkable.and have been made possible by modern large-scale computers. These methods make it possible to carry out an exact numerical calculation of the potential flow around practically any body (see for example [4], [5], [6], [7]) as well as the determination of three-dimensional boundary layers ([8]). In addition, it is possible to solve the two-dimensional Navier-Stokes equations ([9], [10]) within certain limits.

These methods are already competing with the experimental methods. They are superior or equivalent to the latter because of the high model cost. However, they have a limited range of application.

---

(3) Attempts for this have been made possible by the ducted fan turbojet program, which requires, a high-lift catalog" [3].

It is necessary to develop these methods further so that it becomes possible to develop refined predesign methods and to also support work during the concept phase.

By developing the computation methods, it will become possible to use wind tunnels as true research devices to an ever increasing degree. Since in general more reliability is associated with a measured point that has been corrected many times than is associated with the result of a calculation, very often experiments are carried out on a scale which is no longer appropriate with the amount of information the measured data can supply. Certainly it would be an advantage if experimental technology could address itself to problems which at the present time cannot be treated either experimentally or theoretically in a satisfactory manner. Among other things, we should mention the problems of simulating jet engines, the measurement of unsteady or quasi-steady coefficients as well as the numerous unsolved interference problems, as well as the problem of Reynolds number and Mach number corrections.

The not very satisfactory computational and experimental possibilities, which occur in individual cases, limit the accuracy of the data which can be determined in the definition phase. In order not to push these problems into the flight test phase, it will be necessary to build new installations in conformance with the technological state of the art, in addition to increased research activity and better instrumentation for the present wind tunnels.

3. Special Unsolved Problems

3.1. Flight Phases and Flight Ranges

The problems outlined in the preceding sections dealt with the fundamental treatment of aircraft design, and not with special flow problems. Aerodynamicists are confronted with flow problems during preliminary studies or during project work which is in progress. In general, questions are answered for the project by "engineering methods" without interrupting the work flow in a satisfactory manner. Basic research must be performed for a deeper understanding and in order to transfer results to future aircraft.

Such flow problems occur primarily if new flight regimes are to be reached by an aircraft. Figure 2 shows the motion of an aircraft and the following flight phases

takeoff, cruise, maneuver, and landing.

During takeoff and landing, one makes a distinction between conventional, short, and vertical techniques. Unsolved problems are restricted to short and vertical takeoff and landing technology.

The cruise can occur in the subsonic, the supersonic, or the transonic flight regimes. It is assumed that transonic cruise will be especially efficient.

Combat aircraft carry out maneuvers at high subsonic and transonic flight regimes even though they have supersonic

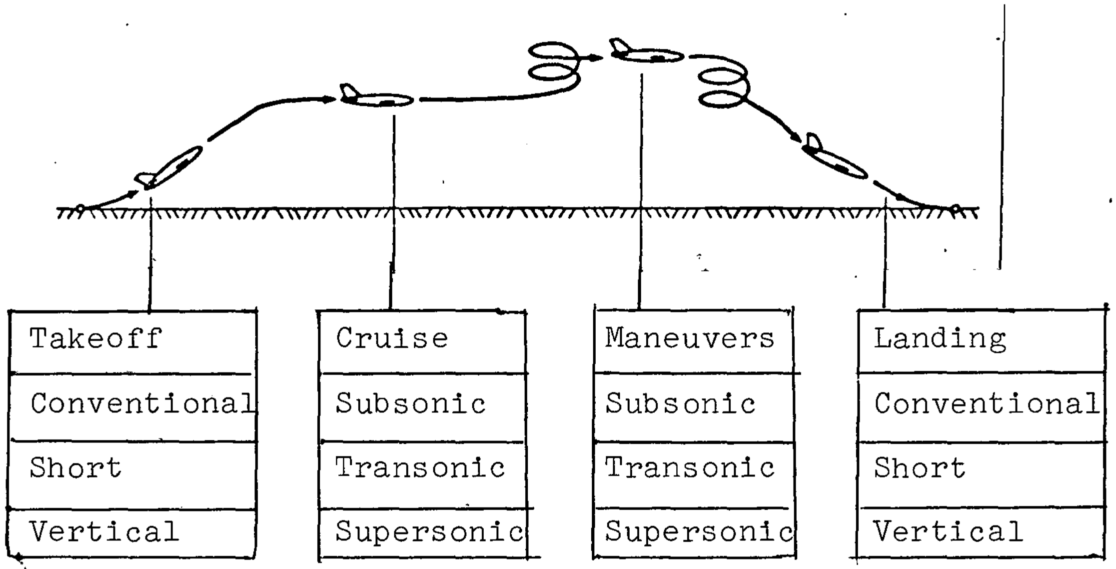

Figure 2. Flight phases. Problem areas

capabilities. The unsolved problems must therefore primarily be looked for in this velocity range.

Several unanswered questions derived from the flight phases depicted in Figure 2 will be discussed in the following sections. These questions have arisen during the design phases and merit intensive investigations.

3.2. Takeoff and Landing

3.2.1. Short Takeoff and Landing Using High-Lift Auxiliary Devices

The development of high-lift aids for improving the takeoff and landing performance of an aircraft belongs to classical technology. Often it is stated that this partial discipline of aircraft development no longer has any unsolved problems. However, it can be argued that the theoretical and experimental work in the area of high-lift aids is still unsatisfactory.

In fact, the flap problem is hardly a clearly defined one, because of the large number of wing, flap and slit parameters, because it is not possible to give a theoretical treatment of the coupling between nonseparated and separated flow and because many problems cannot be settled by experiment using existing experimental test equipment due to the fact that the models are relatively small.

Until larger experimental installations are built, the aircraft prototypes will have to start their test flights with a wide scatter in the take off and landing performance numbers (4). Up to the present, most of the flap development was carried out using numerous measurements with small models, computational approximations and extensive comparisons of measurement data using similar configurations (see for example [3], [11], [12], [13]).

Even though this method of analysis is not satisfactory, it seems that landing technology has been favored as far as flap systems are concerned. In general a flap system is looked upon as favorable if it results in high lift coefficients. This is why most optimization work amounts to finding a flap slit geometry which has the largest maximum lift.

---

(4) High-lift investigations represent one of the central problems for the large subsonic wind tunnel planned in Germany.

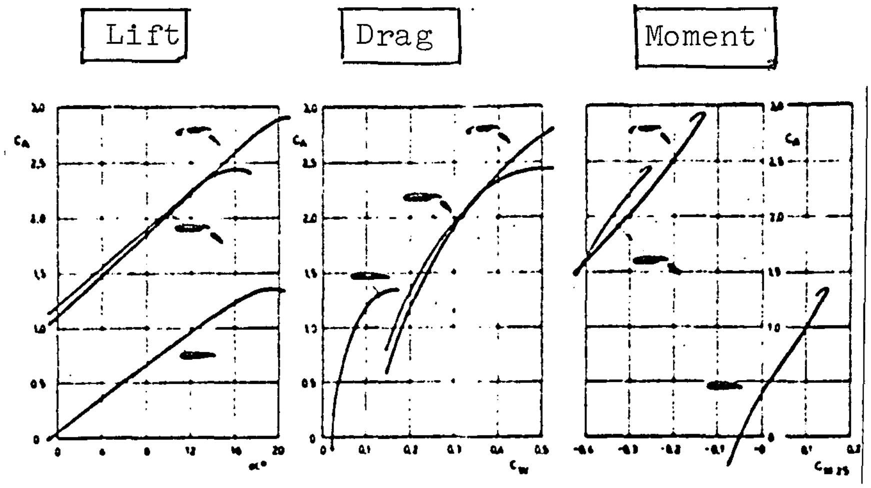

Figure 3. High lift. Influence of trailing edge flap and canard wing

The result of such an optimization for landing is shown in Figure 3. The figure shows measurements made on a wing-fuselage combination of a transport aircraft. The lift coefficient is plotted as a function of the angle of attack, the drag and the pitching moment for the free wing, the wing with a trailing edge flap and the wing with a canard wing and trailing edge aids.

The considerable increase in lift due to trailing edge aids is apparent. It can be increased even more by means of a canard wing. The drag increases considerably when the flap is operated, which is desirable for landing. The flap deflection also brings about a noticeable displacement of the zero moment, which leads to a lift decrease because of trim.

Such a flap system is advantageous for the landing case. If the flap geometry is determined for landing, this will determine the fundamental extension kinematics and will therefore restrict the flexibility of the aerodynamicist as far as adjustment to the takeoff case is concerned.

However, fundamentally different requirements exist for takeoff than is the case for landing. Thus, in the case of commercial aircraft, the aircraft must be able to reach a certain ascent angle after a certain rolling distance if the engines fail. The lift-to-drag ratio at maximum lift represents an appropriate evaluation method if the thrust is reduced and the takeoff weight is constant.

Figure 4 shows such a plot. The reciprocal lift-to-drag ratio is shown as a function of maximum lift at about 1.2 times the stalling velocity, which is about 70% of the maximum lift. The wing has the best lift-to-drag ratio when the flaps are retracted but the maximum lift is small. The best maximum lift is obtained if canard wings are used, but here the lift-to-drag ratio is so small that the flap arrangement can only be taken advantage of with a very large thrust, if the above requirements are met. In the majority of cases the center of the range is selected which is a range in which the canard wing can only be slightly effective. The aerodynamicist therefore is confronted with the unsolved problem of designing flap systems which have high lifts and small drag. This raises the question as to the nature of the drags. This question is answered in Figure 5.

The figure shows the flow around the profile with extended canard wing and extended trailing edge flap. There is a bubble shaped separation of flow along the back side of the canard wing and in the flap section of the wing which is well developed. It disturbs the pressure distribution in the slits and also bring about a wake with a large total pressure loss.

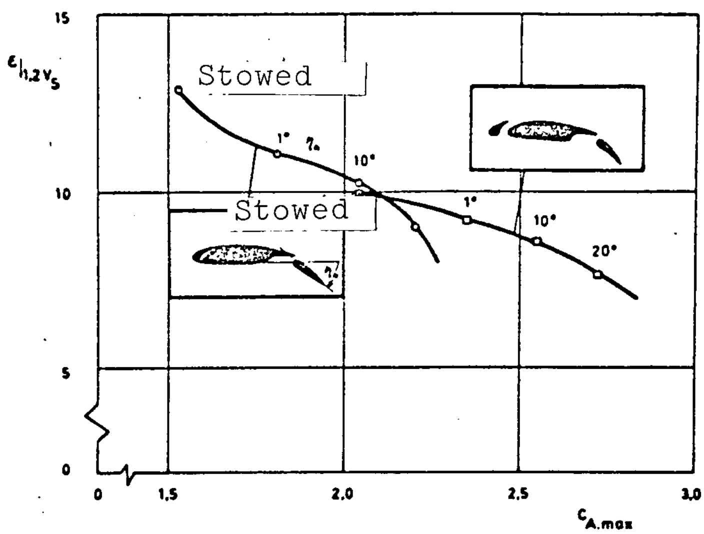

Figure 4. High lift. Lift/drag ratio in the starting configuration

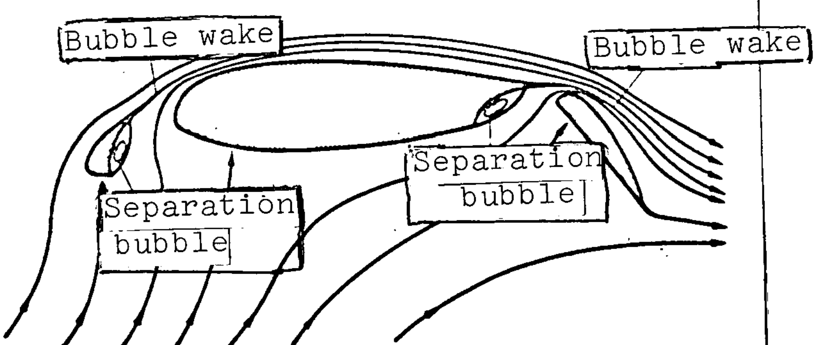

Figure 5. Flow around the profile. Schematic

Not much is known about the nature of the bubbles. It is known that it is not very effective to round off the edges, because the pressure increase in the flow direction and also perpendicular to it will still be very steep. Neither the separation process nor the reattachment mechanism are very well known. Also the question of transferring model measurements to the real aircraft is an unsolved problem.

The separation bubbles seem to be of the same type as are encountered in the short bubbles found on thin wing profiles (see [13], [14]) from which the well known leading edge vortices develop in arrow wings. Vortex-like flows have also been observed in flap slits of sweptback wings.

The theoretical and experimental investigations of bubble-shaped separations have become an acute problem again. Apparently, they cannot be analyzed using the classical boundary layer concept, according to which the pressure gradient normal to the flow direction can be ignored compared with the gradient in the flow direction. Instead, experiments seem to show that the transverse gradient plays the fundamental role and that separations also occur if the flow has a tangential acceleration.

Since integration of the Navier-Stokes equations in laminar flow has been solved for simple cases over the last few years (see [9], [10]), a tool has been developed which should provide an analytical treatment of this unsolved problem. It is possible that a simple boundary layer method can be developed from it, which in contrast to the classical concept would deal with flows in which the pressure gradient in the flow direction plays a smaller role than does the transverse gradient.

3.2.2. Vertical Takeoff and Landing by Jet Support

The development of jet supported vertical takeoff aircraft is generally looked upon as a special achievement of European aircraft technology. The best known vertical takeoff aircraft, such as for example the VJ 101, C, Do 31, VAK 191B, Kestrel and Harrier are products of the European aviation industry. Of these, the Harrier is already being mass produced by Hawker Siddely.

Germany has a substantial amount of experience in the development of such aircraft, which will make it possible for industry to develop large vertical takeoff commercial aircraft. However, this experience has also led to a greater number of unsolved problems.

In treating vertical takeoff problems, it has been found expedient to divide them into purely aerodynamic and thermal effects. The aerodynamic effects can also be explained by means of cold jets. However, the thermal effects describe the influence of hot jets. Both groups of problems are of necessity coupled with each other. Nevertheless, we will treat them separately here.

3.2.2.1. Aerodynamic effects of vertical takeoff aircraft

Figure 6 shows a summary of the important aerodynamic jet effects. In the figure, a division between hovering flight and transitional flight has been made. In the transition phase, one must distinguish between longitudinal and side motion problems.

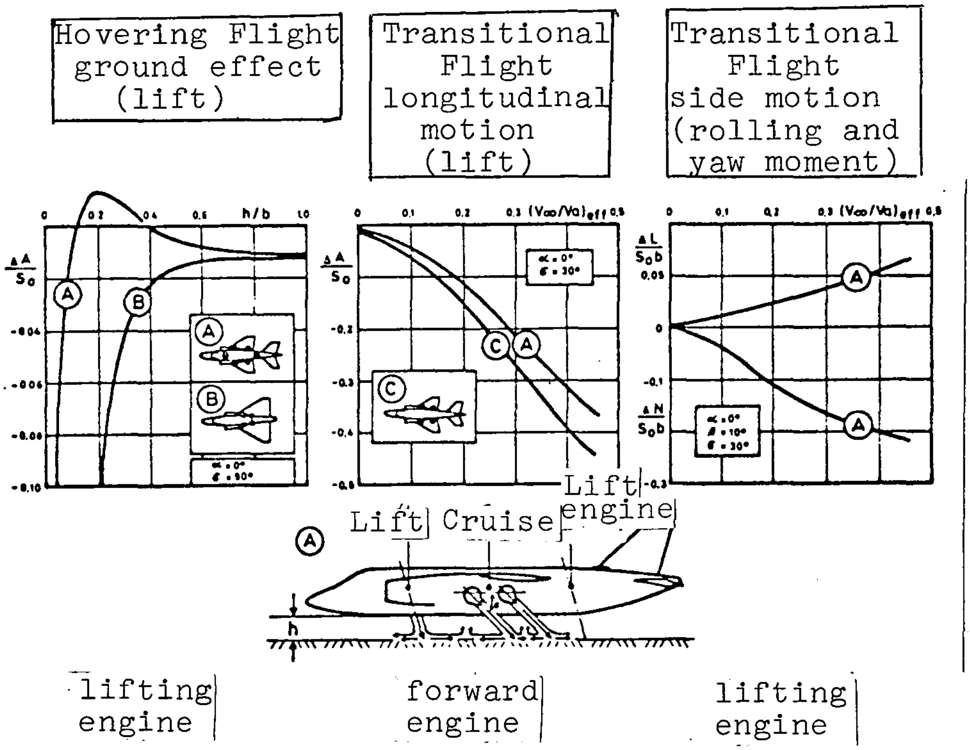

Figure 6. Influence of the Jet. Aerodynamic effects

The figure also shows the learning process in vertical takeoff aerodynamics.

In the first phase the problems of hovering flight were investigated in the vicinity of the ground (see, for example, [15]).

It was found that the suction effect of engine jets leads to substantial lifts and changes in the moment because of continuous mixing with the surrounding air. The suction effect becomes especially great if the jet expands immediately after emerging from the nozzle in the form of a wall or ground jet. If the distance to the ground is small, that is during takeoff, very strong negative lifts are measured.

This is made clear by means of curve B in the left part of Figure 6. Here the loss in lift or thrust Δ A is referred to the ideal thrust S_0 and is plotted as a function of the dimensionless distance to the ground h/b. Here h is the distance from the ground to the lower edge of the aircraft and b is the span of the aircraft. The aircraft B has 4 nozzles which are arranged so close to each other that the jets can be essentially considered as a single jet.

The large negative lift can be seen at small distances from the ground, which makes the takeoff extremely difficult.

However, if the nozzles are separated from each other, then the jets will hit the ground independently and will first be propagated in the form of ground jets. Part of the jets collide underneath the aircraft and mutually deflect each other. Because of this deflection, part of the total exhaust impulse pushes against the lower side of the aircraft in the form of a fountain and produces additional thrust, as is shown by means of curve A.

This additional thrust does make the takeoff of the aircraft easier but, in the case of hot jets, thermal loads of the airframe occur and can lead to overheating of the air drawn in by the engine.

In a second phase, the problem of the suction action of jets during forward flight was investigated when the nozzles were positioned obliquely or perpendicular. In investigating the longitudinal motion (see for example [16], [17], [19]) it was found that the relatively small downward motion of the inhaled air led to considerable local angle of attack and stagnation pressure changes over the wing and tail surfaces because of the reduced forward velocities. Consequently, lift and pitching moment components induced by jets resulted which depend primarily on the type of aircraft, the nozzle deflection angle and the velocity.

The central part of Figure 6 shows a typical example of this. The figure again shows the loss in lift referred to the ideal thrust and is plotted against the so-called effective velocity ratio. By this is meant the square root of the ratio of the momemtum of the incoming air to the momentum of the air emerging from the nozzles. If the density differences between the jets and the air are small, then the effective velocity ratio corresponds to the ratio of the forward and average jet velocity.

The figure shows the measured values for two aircraft A and C, the forward engines of which were deflected by 30°. In one case, two almost perpendicular lifting engines were turned on (case A) and in the second case (case C) they were turned off.

It can be seen that at the end of transition, i.e., for a velocity ratio of about 0.3 to 0.4, still 20 to 40% of the thrust is lost because of aerodynamic effects. However, one cannot ignore the fact that the wing lift increases as the square of the velocity, and therefore the thrusts of the lifting engines could be throttled or the forward engines could be turned even more.

Nevertheless, the optimization of a transition process represents one of the most demanding problems of flight mechanics because of the many operational conditions and the continuous changes in the lift, drag and especially the longitudinal moment, which depends on a large number of parameters.

The third phase in the investigation of jet problems of vertical takeoff aircraft is concerned with the jet induction for the side motion. The same effects, which lead to lift decreases and tipping moments when the longitudinal motion is considered, also influence the rolling and yawing behavior of the aircraft.

The right parts of Figure 6 show the rolling and yaw moment induced by the jet as a function of the effective velocity ratio. They depend primarily on the angle of sideslip. There is a substantial improvement in the wind vane stability, as can be seen from the negative yaw moment. However, there is a degradation in the roll stability, as the positive rolling moment shows. Therefore, the influence of the jet is to improve the wind vane stability and deteriorate the roll stability. The knowledge of these effects is decisive for adapting the attitude control system during the project phases. Several accidents with vertical takeoff aircraft can be explained by non-controllable rolling motions which occurred at angles of sideslip which were too large. Wind vanes in the direct field of view of the pilot for controlling the angle of sideslip represent temporary measures, which, however, limit the independence of the vertical takeoff and landing operation from the wind direction.

The theoretical and experimental clarification of these effects, which are decisive at the project level, still represent unsolved problems. Models, which have been found to be useful in the case of jet-induced lift, should be further expanded in order to at least establish limits for experiments.

Figure 7 shows two of these models. The left part of the picture shows a sink model and the right part, a vortex model. Both methods attempt to find a theoretical potential replacement model for the jet which can be used to represent the suction effect.

In the case of the sink model (see [16]), the surface of the jet is covered with sink elements which result in the measured intake velocities and maintain the circular shape. Since the main part of the inductions at the wing come from a region in which the jet has not yet been considerably distorted, the distortion of the jet axis and jet cross section are neglected, and the sinks are placed on a semi-infinite cylinder or cone. This is why the model is especially suited for representing the near field, i.e., the flow around the wing.

The velocities induced by this covering by sinks result in normal and tangential components at the location of the wing. The normal components are equalized by means of additional wing circulation, have the effect of an apparent negative curvature, and result in a lift force. The tangential forces bring about a jet-induced stagnation pressure change and result in a change of the lift increase.

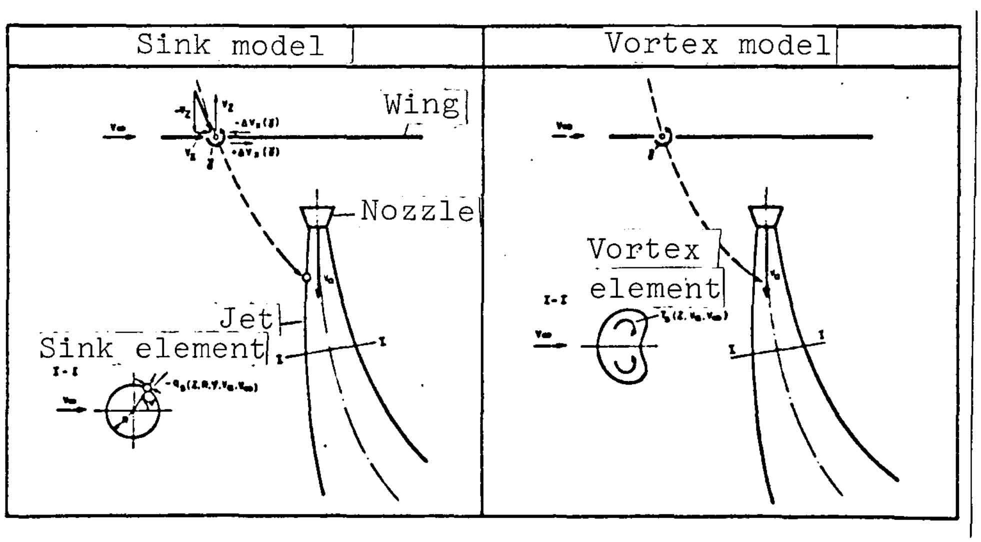

Figure 7. Lifting jets. Replacement models

In the case of the vortex model (see [18]) one begins with the fact that the jet cross section is deformed in the shape of a kidney when subjected to cross flow as the distance is increased. Two opposing vortices are formed inside the jet and these vortices represent the entire jet when viewed from a large distance. A theoretical potential replacement models results using the empirically determined axis deformation found in [19] and by extrapolating the vortex circulation in the direction towards the nozzle, which primarily represents the far field and is especially well suited for determining the jet induction, for example, at the elevators.

Both models are relatively simple and can be used for treating sliding wing-fuselage combinations.

3.2.2.2. Thermal effects in vertical takeoff aircraft

The thermal effects for vertical takeoff aircraft are primarily coupled with the hovering flight phase. The most important problems during this phase are the heating of the airframe and the suction of hot air by the engine intakes. The airframe heating leads to materials and construction problems and therefore directly affects the weight and costs. The suction of hot gases by the engine represents a danger and also represents a source of a considerable thrust loss [5].

The physical problem is shown in Figure 8. The figure shows an aircraft at a small hovering altitude. Some of the hot gases

---

[5] As a rough approximation, a 10° C temperature change means 2% thrust loss for conventional engines.

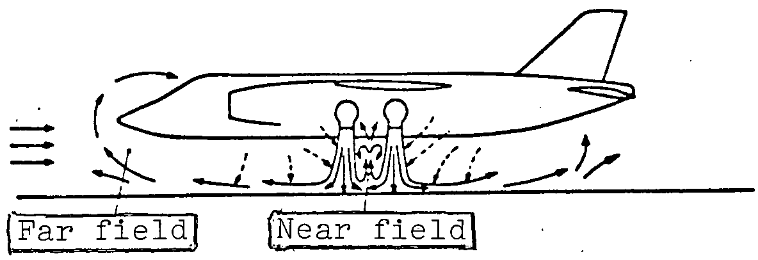

Figure 8. Influence of the jet

are transported back to the aircraft between the two thrust jets, that is, in the so-called near field. This transport back to the engines occurs along the fountains mentioned above. The jets traveling along the ground can be separated in the far field from the ground because of unfavorable wind conditions and can also be swept back to the aircraft. Finally, if the holding times are long, the hot jets can heat up the surroundings so much that a heat bell is formed around the aircraft which will continue to decrease the thrust.

The two cases just mentioned above are not very critical during normal aircraft operation. They deal with the question of how to direct large amounts of air at a low temperature increase. On the other hand, the control of the high temperatures in the fountain upstream and the transfer of results from model experiments to the full-size version of the aircraft represent critical problems.

Figure 9 shows the scope of the unsolved questions. The figure shows the flow along the ground of aircraft A (see section

3.2.2.1) for a moderate hovering altitude. The shape of the aircraft and the exhausts of the six jets were drawn on the ground plate. The stagnation areas of the forward engine jets and of the two obliquely mounted lifting engine jets can be clearly seen. The individual ground jets intersect along the solid line shown in the diagram, the so-called downwash lines. The flow is deflected upwards at each center of the downwash lines. This is the point at which the fountains mentioned several times originate.

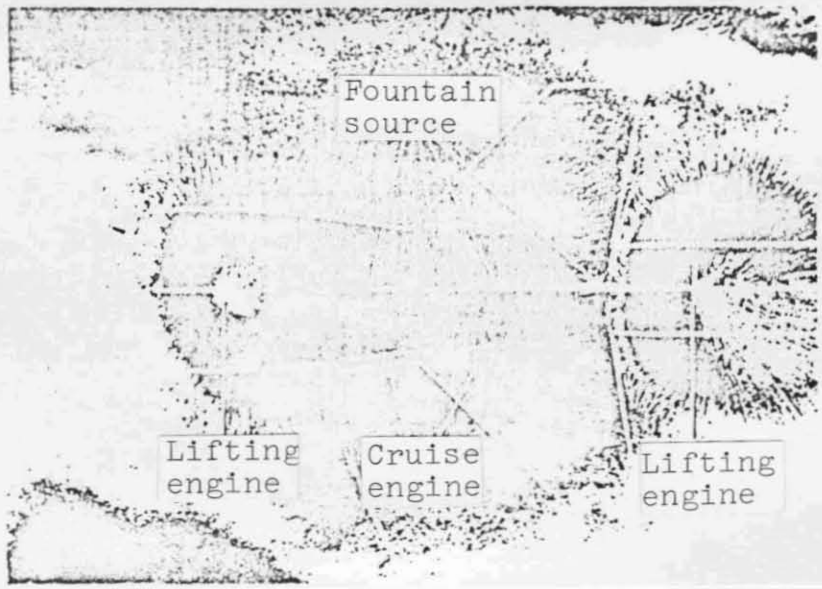

Figure 9. Jet influence. Ground flow

The deflection of converging ground flows, which lead to a departure from the ground, is not stable. This is why a pronounced vortex is always superimposed on the upstream.

The production of these vortices corresponds to the so-called intake vortices, which can be noticed by passengers between the ground and the intake or between the fuselage and the intake during wet weather. The intensity of the vortex can be so great that rocks can enter the intake if the engine is mounted low enough.

Up to the present, not much is known about the stability of such upstreams. However, it is known that the conditions in the nozzle and the nature of the ground will naturally have a large effect.

This is why investigations must lean heavily on experiment. In spite of the technological problems of building models for the determination of high temperature differences, the adjustment parameters for the engine nozzles are of primary importance.

Just as was the case for the jet induction problems in the preceding section, the specification of average values by the engine manufacturers does not satisfy the requirements of the aerodynamicist. It can be shown that the fountain formation in the case of jets having an ideal rectangular profile at the nozzle exhaust differs considerably from what happens in a realistic jet profile.

This leads to a restriction of the information which the expensive experiments can furnish. This is unfortunate, because it is just recently that significant advances in similarity mechanics have been made. The problem of transferring measurements made with models to the final version of the aircraft should be completely solved in the near future [20].

3.3. Transonic cruise

Transonic flight has become interesting during the last few years. The airline companies feel that flight at a Mach number of $M_\infty \approx 0.95$ will result in a more profitable future than flight at moderate supersonic velocities. Certainly the unsolved problems of the supersonic boom play an important, but not a dominating role here.

In order to continuously increase the cruise velocity of commercial aircraft, aerodynamicists have used the following two methods. The wing sweepback has been increased, and the relative profile thickness has been decreased. Both methods make it possible to maintain the subsonic velocity for a longer time over the wing. Both methods also cause the weight to increase and have a detrimental effect on the takeoff procedure, which is why there is an economic limit to these methods. The fact that conventional profile families have few agreeable aerodynamic properties as soon as local supersonic velocity fields occur over the wing represents another piece of practical experience. In order to stop this process, it was therefore necessary to develop new profile families, which show a more neutral behavior with respect to local supersonic fields. These are the so-called transonic profiles.

Figure 10 shows their planned performance as compared with that of a normal profile.

The normal profile in the left part of the picture is essentially a so-called laminar profile. At high subsonic velocities characterized by the Mach number $M_{\infty,1}$, profiles of this type have favorable properties because of the flat pressure

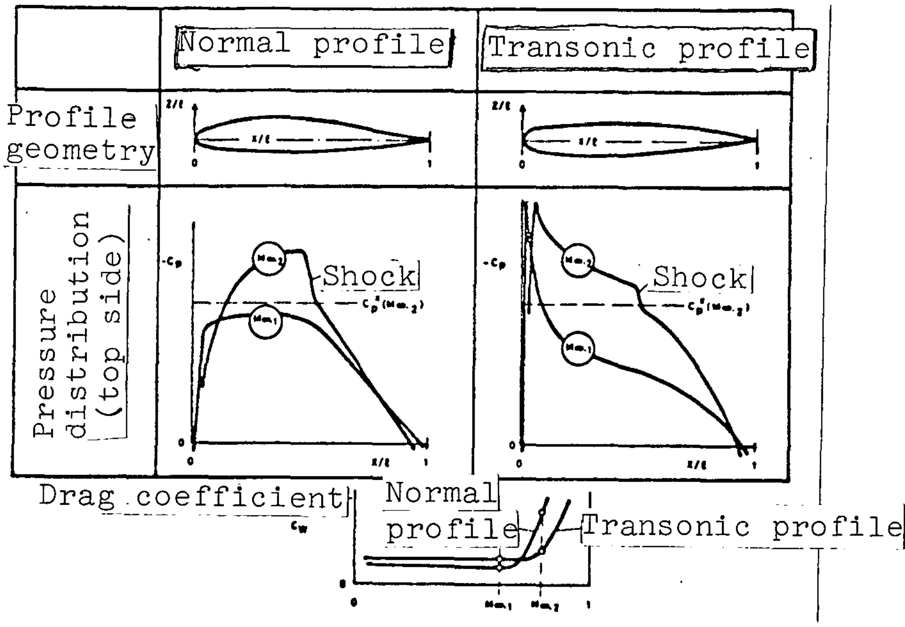

Figure 10. Normal and Transonic Profile. Comparison

distribution brought about by the laminar conditions. After the critical Mach number is exceeded, a supersonic field rapidly develops which is terminated by means of a powerful shock. As a consequence of this, there are drag increases, changes in moments and changes in lift due to the interaction of boundary layer and compression shock, which occur to a greater or lesser extent.

In the experimental investigation of profiles in flows close to the speed of sound, Pearcy [21] discovered that a local supersonic field created by a sharp suction tip can be closed by means of a weak compression shock instead of by a strong shock. This fact could only be clarified by a field of isentropic recompression before the shock. Isentropic recompression did however contradict classical theory, until Nieuwland [22] and others gave theoretical and experimental proof of this using specially designed profiles. In the meantime, the concept of isentropic recompression has been found to have technical application. An attempt is made to find profile families which approximately correspond to the right part of the pressure distribution in the figure.

The pressure distributions of the normal profile and transonic profile shown in Figure 10 are valid for the top side and correspond to the same Mach numbers. In the subsonic range ($M_{\infty,1}$) the pressure distribution of the normal profile is more favorable. This is shown by the course of the drag in the lower part of the figure. In the transonic range ($M_{\infty,2}$), the normal profile becomes unfavorable or even unusable. On the other hand, the transonic profile has a field of isentropic recompression with a weak termination shock over a wide region. It is more favorable at this Mach number, as the course of the drag curve shows.

The physical concept of isentropic recompression is shown in Figure 11. The left part shows the pressure distributions of the transonic profile again, and the dashed curve shows the corresponding distribution for the normal profile. The sonic line is shown in the right part of the figure, which separates the supersonic and subsonic fields. If it is possible to trigger a directed expansion fan at the tip of the profile, then the waves will be reflected at the sonic line in the form of compression waves in the manner shown. They will then return to the profile and build up the underpressure in an isentropic way.

In order to be able to apply transonic profiles in practice, the following questions remain to be answered:

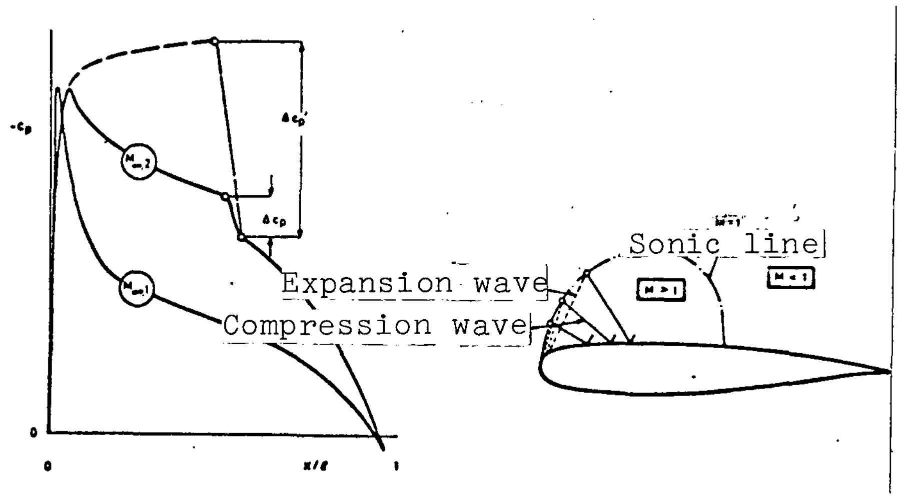

Figure 11. Transonic profile. Isentropic recompression

First of all it is necessary to understand the mechanism of isentropic recompression so that a practical design tool is created. At the present time, this has not been done, because the laws in the local supersonic field have not yet been sufficiently clarified (see for example [23]).

In addition, the general calculation of plane flows with supersonic and subsonic acoustic fields encounters mathematical and numerical problems. Nevertheless, advances have been made in this area because extensive differencing methods for the treatment of the nonlinear differential equations which represent the flow can be applied using existing computer installations ([24], [25], [26]).

Some of the known methods avoid the problem of solving local elliptical, parabolic or hyperbolic differential equations by operating in a pseudostationary way [26].

In this case, one takes advantage of the fact that the unsteady potential equation is always of the hyperbolic type. These methods then formally calculate the temporal establishment of the flow field. They then use the asymptotic state, which develops after a number of steps, as the steady solution.

3.4. Maneuvering Flight in the Subsonic and Transonic Flow Regime

In spite of the fact that they have supersonic capability, military aircraft practically always maneuver in the high subsonic or transonic flow field regime. The load factors change as the altitude ranges change.

The maneuver spectrum can be limited in certain ways. Lines corresponding to the limitations are shown in Figure 12. The maximum lift as a function of Mach number, determined from wind tunnel measurements and which are described by curve A, represent the uppermost limits. The corridors determined for the load factors n = 1 and n = 4, and which depend on the area loading and flight altitude, intersect this curve at certain flight velocities. In the present case, it is just possible to fly at $M_\infty = 0.25$ in the horizontal direction in the vicinity of the ground.

Whether or not this or another velocity can be flown depends on the available thrust and the drag of the aircraft. This limit therefore depends on the engine, and is not shown in Figure 12.

This figure also does not show the stability and controllability. Of course it is clear that a lift coefficient can only be flown if the aircraft satisfies the minimum stability

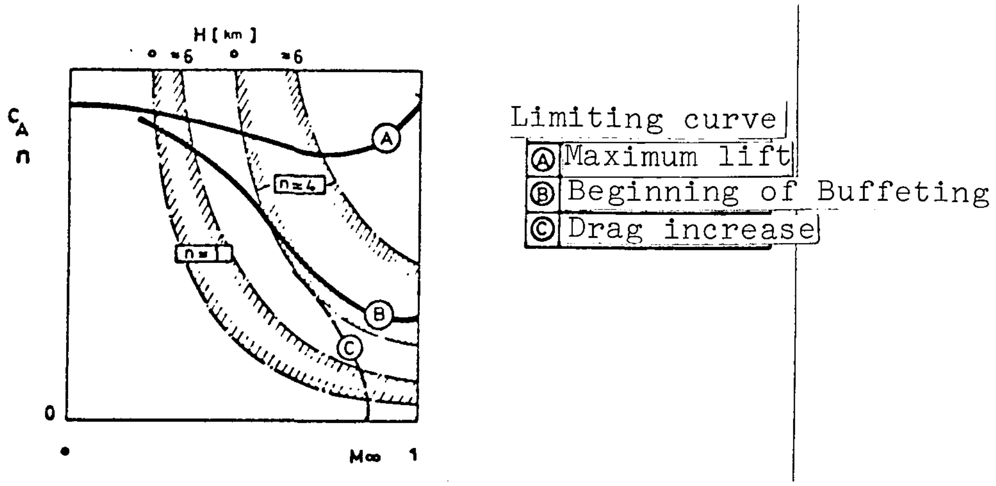

Figure 12. Maneuvering flight. Limiting ranges

requirements and at the same time it must be in the position of compensating for these coefficients using the rudders.

Instead of this, curve C shows the course of the drag increase. This curve demonstrates the problem of transonic cruise, mentioned in the previous chapter. It can be seen that the important maneuvers occur at lift coefficients which are above the drag increase. Independent of the question of whether profile geometry plays a dominating role in the case of low aspect ratio sweptback wings, it becomes clear that the design for cruise conditions will influence the maneuver capabilities only slightly.

The line corresponding to the beginning of buffeting, the so-called buffeting line (curve B), is an important curve shown in Figure 12. The buffeting can have many origins and consequences. Here we will limit ourselves to stating that it is due to the interaction of the boundary layer and the compression shock. Thus the problem essentially reduces to finding the correspondence between Mach number and lift coefficient for a given wing for which the boundary layer separates at the root of the compression shock (see for example [27]).

Observations have shown that in this correspondence, the compression shock — separation point system must be displaced around a central location. Continuous fluctuations in the circulation and wake with corresponding large stresses on the pilot and the structure must therefore be expected.

As the velocity is decreased, the buffeting line is displaced in the direction of the maximum lift curve. In the transonic range, it can be located at such small lift values that is is no longer possible to make the transfer from the subsonic to the supersonic velocity without buffeting.

In addition to further research on the described flow mechanism, one of the goals of aircraft development will be to develop wings having high buffeting limits.

For the aerodynamicist, the slender delta wing already represents a wing shape for which buffeting and lift limit are close to each other, according to experience. Therefore, considerable differences are to be noted in the flow around delta wings and classical sweptback wings.

The differences are shown in Figure 13. The figure was produced from flow visualization images* and is valid for a typical maneuver case. The left part of the figure shows a delta wing with a small aspect ratio and therefore a large sweepback. The right part of the figure shows a classical arrow wing with moderate aspect ratio and small sweepback.

---

*Translator's Note: Literally, "paint" images.

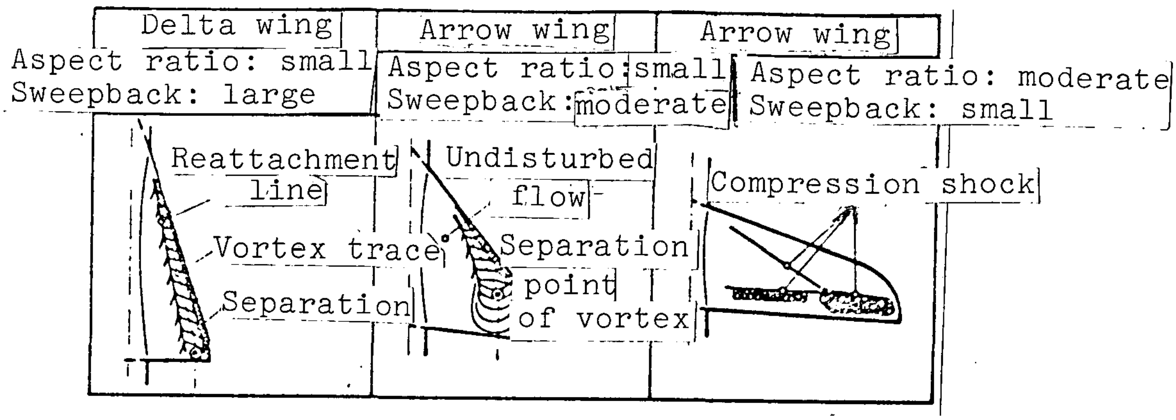

Figure 13. Types of flow. $M_\infty = 0.85$, n = 4

The flow visualization image of the delta wing is primarily governed by the leading edge vortices which are typical for these wings. It is known that the flow separates at the leading edge in the form of a stable vortex band or pipe vortex, which increases with the path distance. The vortex axis lies above the wing plane. The rolling up occurs already at small angles of attack, and is the reason for the nonlinear behavior of the coefficients.

Air is sucked from the surrounding region underneath the vortex because of the strong underpressure in the vortex band. The trace of the separation flow surface, which forms the boundary between the interior region of the wing and the effective region of the pipe vortex, is called the reattachment line.

Therefore, the flow around a delta wing is fundamentally different than the flow around a classical arrow wing. The flow field of an arrow wing with moderate aspect ratio and small sweepback can essentially be explained by the flow around the profile. One or more shock fronts run transversely over the wing and bring about a strong separation field in the area of the trailing edge when the maneuver loads are present. One can hardly expect favorable maneuver behavior under these conditions.

Therefore, for maneuvering the delta wing flow is preferable over the flow behavior of a classical arrow wing. The arrow wing has other advantages, which must still be mentioned. The aerodynamicists therefore attempt to develop a wing type which represents the right compromise between the two shapes.

At small load factors, this wing type should behave as a conventional arrow wing, but, as the angle of attack is increased, it should take on the flow behavior of a delta wing in a continuous way. Therefore it will have an aspect ratio which is smaller than that of the arrow wing but still larger than that of the delta wing. Its sweepback will be adjusted according to the aspect ratio and therefore will certainly be smaller than in the case of the delta wing, but larger than in the case of a classical arrow wing. In addition, the fuselage must be considered in the design, and the shoulder covering arrangement shows certain advantages in this respect.

The central figure of Figure 13 shows such a wing shape. The appearance of its flow is quite similar to that of a delta wing for maneuver load conditions. The leading edge vortex also occurs here. However, this vortex is not built up by separated flow up to trailing edge. Depending on the angle of attack and Mach number, a separation point of the vortex appears at which point the contact with the leading edge is broken. After this point the vortex is a free vortex above the wing surface, and influences the coefficients of the wing and the wake properties in a significant way.

The calculation of these flow types is still an unsolved problem for the most part. The calculation methods for a non-linear flow over delta wings, see for example [29], [30], [31], are not able to describe the flow mentioned above, nor can the method of Gersten [32] do this. Experimental investigations have only been performed for special cases and have usually not been published. Wind tunnel measurements do confirm the continuous transition from the arrow wing flow to the quasi-delta wing flow and show that wing buffeting appears only for load factors which can no longer be flown by the pilot.

The development of future maneuvering wings will certainly lead to wings of the type described above. However, restrictions will have to be made in other disciplines of aircraft technology, or special measures will have to be taken, which will be the logical result of the disadvantages of the maneuvering wing. This is indicated in Figure 14, which compares the coefficients of an aircraft with maneuvering wings and an aircraft with classical arrow wings in subsonic flow.

If we first compare the lift curves without flaps, then it can be seen that an aircraft with maneuvering wings can produce substantially larger maximum lifts. The fuselage can provide an appreciable contribution to this.

The maximum lift is attained at very large angles of attack, which cannot be used during takeoff and landing. If both configurations have flaps, then the gain for the arrow wing is considerable. In addition it operates in a region which is favorable for takeoff and landing. The lift of the maneuvering wing, on the other hand, can only be improved slightly because of its smaller span and greater sweepback.

A comparison of the drag of both wing shapes also leads to a preference for the arrow wing. The nonlinear flow affects the drag to an ever-increasing degree. For the maneuver wing, the aerodynamicist can penetrate into the leading edge vortex by means of a simple nose flap and therefore bring about a relatively substantial reduction in drag. This is why it is appropriate to provide these wings with nose flaps.

Just like the delta wing, the maneuver wing also has a pitching moment course which is self-stabilizing. If tailplane positions are avoided where the elevator is inside a developed vortex field, then configurations are obtained which become more stable as the lift is increased. The maximum load factor is then neither limited by buffeting nor by instabilities. Instead it is limited by the rudder area, strength, and engine thrust.

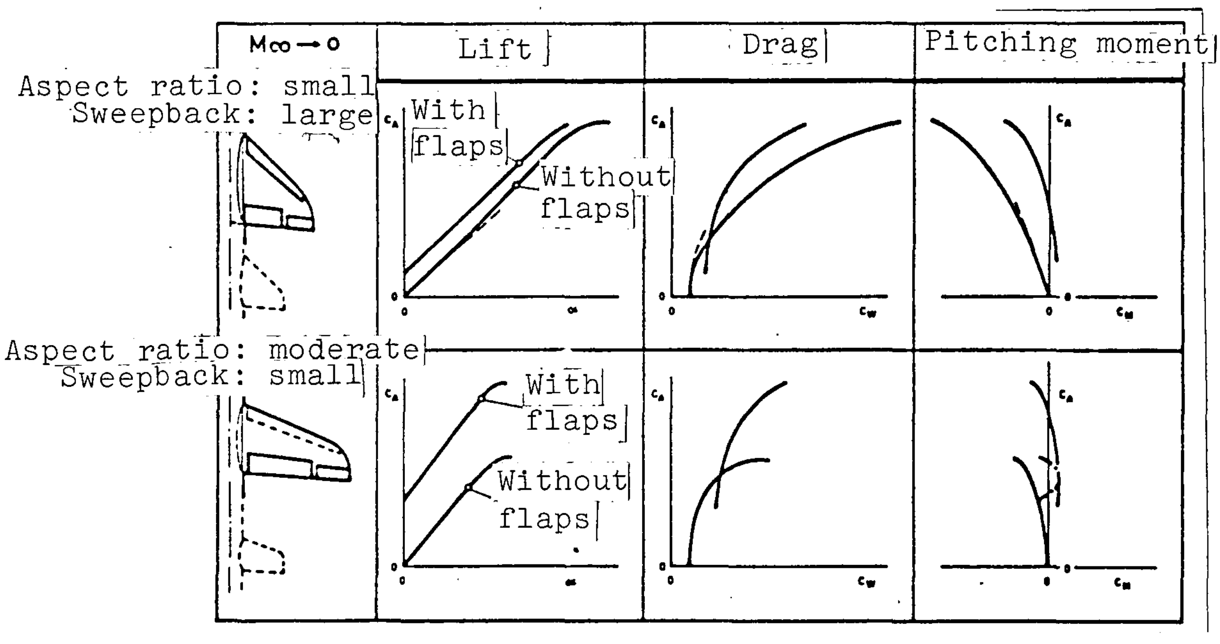

Figure 14. Arrow wings. Comparison of coefficients

On the other hand, classical wing profiles are often not self-stabilizing and special care is necessary for the tailplane, in order to have stability in all flight regimes.

As far as the aerodynamic evaluation is concerned, the maneuver wing has clear advantages over the classical arrow wing. One of its disadvantages is that the flaps are not very effective, which is not too important for vertical takeoff aircraft and it should be possible to restrict it to the high lift problem by performing further research.

4. Summary

Unsolved problems accompany the aerodynamicist through all stages of aircraft development, just as is the case for most engineers and researchers. They can be divided into current project work and problems for future project work.

The problems connected with current projects deal with the gaps in the theoretical and experimental description of known flow types. They make the aerodynamicist use new computation methods, improve his experimental methods, expand available installations, or to even build new research equipment.

The problems associated with future projects show how much interest there is for understanding interesting flow processes. These are the research problems which should be solved in the near future in order to satisfy the increased technological requirements of future aircraft. Some of these questions were described and others are collected in a table in the Appendix.

Each of these problems can be solved with a moderate amount of effort and none of them is unimportant for the development of aircraft technology.

5. References

Note: The literature cited here only give a fraction of the total publications available in each special field. Further references can be found in the following papers.

1. USAF Stability and Control Datcom, AFFDL (FDCC), Wright-Patterson Air Force Base, Ohio.

2. Aerodynamic Data Sheets, The Royal Aeronautical Society, London.

3. Hochauchtriebs-Katalog (High Lift Catalog), ZTL-Gemeinschaftsaufgabe "Hochauftrieb:, FAG 4, 1969 - 1971.

4. Hess, J. L. and A. M. O. Smith. "Calculation of Non-Lifting Potential Flow about Arbitrary Three-Dimensional Bodies," Report No. E. S. 40622, Douglas Aircraft Co., Inc., 1962.

5. Woodward, F. A. "Analysis and Design of Supersonic Wing-Body-Combinations," NA SA CR-73106.

6. Klevenhusen, K. D. "Kurzbeschreibung der dem Programm PFAATDB zugrunde liegenden Theorie" (Short Description of the Theory at the Basis of the PFAATDB Program) (Surface Method), VFW-Ea-KB 264 (unpublished).

7. "Method for Predicting the Pressure Distribution on Swept Wings with Subsonic Attached Flow", Transonic Data Memorandum TDM 6312, 6312/1, 1963.

8. Walz, A. and D. Deropp. "Entwicklung und Erprobung eines Berechnungsverfahrens für dreidimensionale Grenzschichten" (Development and Testing of a Calculation Method for Three-Dimensional Boundary Layers), ZTL-Teilaufgabe VFW 4.04,(1970.

9. Fromm, J. E. "Numerical Solution of the Navier-Stokes Equations at High Reynolds Numbers and the Problem of Discretiziation of the Convective Derivatives", AGARD-LS-34-71, 1971.

10. Wirz, H. J. "Die laminare Umströmung einer nichtangestellten Platte bei grossen Reynoldszahlen" (The Laminar Flow Around a Plate at Zero Incidence for Large Reynolds Numbers), Dissertation, TU Berlin, 1971.

11. "High Reynolds Number Subsonic Aerodynamics", AGARD-LS-37-70, 1970.

12. "Assessment of Lift Augmentation Devices", AGARD-LS-43-71, 1971.

13. Hancock, G. J. "Problems of Aircraft Behaviour at High Angles of Attack", ADARDograp 136, 1969.

14. Tani, I. "Low-Speed Flows Involving Bubble Separations", Progress in Aeronautical Sciences, Vol. 5, Pergamom Press, 1964.

15. Seibold, W. "Untersuchungen über die von Hubstrahlen an Senkrechtstartern erzeugten Sekundärkräfte" (Investigations of the Secondary Forces produced by the Sustaining Jets of Vertical Takeoff Aircraft), Jb. d. WGL, 1962.

16. Barche, J. and G. Krenz. "Strahleinfluss an V/STOL-Flugzeugen im Übergangs- und Hochgeschwindigkeitsflug" (Jet Influence for V/STOL Aircraft During the Transition and High Velocity Flight Regime), Luftfahrttechnik/Raumfahrttechnik 15, No. 5, 1969.

17. Schulz, G. and G. Viehweger. "Sekundärkräfte an einem Senkrechtstarter mit Triebwerksstrahlen beim Schwebe- und Transitionsflug mit Berücksichtigung des Bodeneffektes" (Secondary Forces in a Vertical Takeoff Aircraft with Engine Jets During Hovering and Transitional Flight Considering the Ground Effect), WGLR Yearly Meeting, Karlsruhe, Contribution 72, 1967.

18. Wooler, P. T. "On the Flow Past a Circular Jet Exhausting at Right Angles from a Flat Plate or Wing", J. roy. aeronaut. Soc., March, 1967.

19. Williams, J.,and M. V. Wood. "Aerodynamic Interference Effects with Jet-Lift V/STOL Aircraft under Static and Forward-Speed Conditions", Z. f. W., July, 1967.

20. Behnert, R. "Bodeneffekt bei strahlgestutzten Senkrechtstartern" (Ground Effect for Vertical Takeoff Aircraft Supported by Jets), ZTL-Bericht FAG 4, VFW-Fokker 4.10/70, 1970.

21. Pearcy, H. H. "The Aerodynamic Design of Section Shapes for Swept Wings", Adv. in Aeronaut. Sc., Vol. 3, Pergamom Press, 1962.

22. Neiuwland, G. Y. "The Computation by Lighthill's Method of Transonic Potential Flow around a Family of Quasi-Elliptical Aerofoils", NLR-TR.T 83, September, 1964.

23. Hansen, N. "Untersuchungen am Übershallfeld bei transsonischen Profilumströmungen" (Investigations of the Supersonic Field for Transonic Flows around Profiles), DFVLR, Report No. 0670, 1971.

24. Cole, J. D. "Calculations of Transonic Flows", ICAS Paper No. 70 - 12, 1970

25. Murmann, E. M.,and J. D. Cole. "Calculation of Plane Steady Transonic Flows", AIAA Paper No. 70 - 188, 1970.

26. Magnus, R. and H. Yoshihara. "Inviscid Transonic Flow over Airfoils", AIAA Journal, Vol. 8, No. 12, December, 1970.

27. Thomas, F. "Ermittlung der Buffeting-Grenzen von Tragflügeln" (Determination of the Buffeting Limits of Lifting Wings), Dornier Report No. 65/6, 1965.

28. Hummel, D. "Zur Umströmung scharfkantiger schlanker Deltaflügel bei grossen Anstellwinkeln" (The Flow around Sharp-Edged and Slender Delta Wings at Large Angles of Attack), ZfW 15, Issue 10, 1967.

29. Küchemann, D. A Non-Linear Lifting Surface Theory for Wings of Small Aspect Ratio with Edge Separations", R.A.E. Rep. Aero 2540, A.R.C. 177769, April, 1955.

30. Mangler, U. W. and J. H. B. Smith. "Calculation of the Flow Past Slender Delta Wings with Leading Edge Separations", R.A.E. Rep. Aero 2593, A.R.C. 19634, May, 1957.

31. Smith, J. H. B. "Improved Calculations of Leading-Edge Separation from Slender Delta Wings", R.A.E. T.R. No. 66070, March, 1966.

32. Gersten, K. "Nichtlineare Tragflächentheorie" (Non-Linear Lifting Surface Theory), Professor's acceptance thesis, Institute for Fluid Dynamics of the Technical High School Braunschweig. Report 59/30, 1959.

6. Appendix

SUMMARY OF AERODYNAMIC RESEARCH PROBLEMS
FOR THE DEVELOPMENT OF FUTURE AIRCRAFT

Flight phase/ flight regime	Topic	Application area		
		Commercial/ transport	Fighter	Sport/ training
Short and vertical takeoff and landing	High lift systems			
	Flap systems	X	X	X
	Influencing the boundary layer	X	X	
	Aerodynamics of high angles of attack	X	X	X
	Aerodynamic jet influence			
	Hovering transitional flight	X	X	
	Cruise flight	X	X	X
	Thermal jet influence			
	Near-,far-field effects	X	X	
	Similarity mechanics	X	X	
	Propeller theory	X	X	X

(Table continued on following page)

Appendix (continued)

Flight phase/ flight regime	Topic	Application area		
		Commercial/ transport	Fighter	Sport/ training
Subsonic/ transonic	Profile theory			
	Transonic profiles	X	X	
	Flap profiles	X	X	X
	Transonic wings			
	Large aspect ratio	X		X
	Small aspect ratio		X	
	Interference			
	Wing-fuselage-tailplane	X	X	X
	Engine-airframe	X	X	X
	Nonlinear flow			
	Wing buffeting	X	X	X
	Maneuver problems		X	
	Unsteady flow			
	Damping coefficients	X	X	X
	Flutter	X	X	X
	Design methods	X	X	X
	Engine intakes	X	X	X

(Table continued on following page)

Appendix (Continued)

Flight phase/ flight regime	Topic	Application area		
		Commercial/ transport	Fighter	Sport/ training
Supersonic	Stability-control		X	
	Interference			
	Wing-fuselage-tailplane		X	
	Downwash		X	
	External loads		X	
	Unsteady flow			
	Damping coefficients		X	
	Flutter		X	
	Design methods		X	
	Engine intakes		X	
Fluid dynamic funda- mentals	Three-dimensional compressible boundary layers	X	X	X
	Flow with separation	X	X	X
	Navier-Stokes-Integration	X	X	X
Experimental installa- tions	Large subsonic wind tunnel			
	Influence of large Re numbers	X	X	X
	V/STOL Technology	X	X	X
	Flutter	X	X	X
	Rotors	X		X

(Table concluded on following page)

Appendix (Concluded)

Flight phase/ flight regime	Topic	Application area		
		Commercial/ transport	Fighter	Sport/ training
Experimental installations	Unsteady flows, damping coefficients	X	X	X
	Flow field measurement	X	X	X
	Engine simulation	X	X	X

Translated for National Aeronautics and Space Administration under Contract No. NASw-2035, by SCITRAN, P. O. Box 5456, Santa Barbara, California 93103.